AD-A113 699 HARRY DIAMOND LABS ADELPHI MD F/G 20/9
ON THE NONLINEAR CONDUCTIVITY TENSOR FOR AN UNMAGNETIZED RELATI--ETC(U)
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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER HDL-TR-1970	2. GOVT ACCESSION NO. AD-A113 699	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) On the Nonlinear Conductivity Tensor for an Unmagnetized Relativistic Turbulent Plasma		5. TYPE OF REPORT & PERIOD COVERED Technical Report
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Howard E. Brandt		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Harry Diamond Laboratories 2800 Powder Mill Road Adelphi, MD 20783		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Program Ele: 6.11.01.A
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Army Materiel Development and Readiness Command Alexandria, VA 22333		12. REPORT DATE February 1982
		13. NUMBER OF PAGES 29
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

HDL Project: A10125
DRCMS Code: 611101.91A0011
DA Project: 1L161101A91A

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Plasma turbulence
Nonlinear conductivity
Dissipation
Symmetries
Relativistic plasma turbulence
Plasma physics
Bremsstrahlung

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The symmetry properties of the second-order nonlinear conductivity tensor for an unmagnetized, relativistic, and weakly turbulent plasma are important in the analysis of the collective bremsstrahlung instability. This tensor has some exact symmetries that, if resonant wave-particle interactions are neglected, become the widely known symmetry related to the Manley-Rowe relations, crossing symmetry, and the nondissipative nature of the

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20. ABSTRACT (Cont'd)

nonlinear current. Using the well-known expression for the conductivity from plasma turbulence theory, a polynomial representation for the tensor is obtained in which all derivatives are removed and the pole structure is clearly exhibited. The exact symmetries are obtained by a lengthy algebraic reduction using this representation.

CONTENTS

1. INTRODUCTION

The nature of the collective bremsstrahlung instability and its possible importance to plasma astrophysics and relativistic beam-plasma systems has been explored in considerable detail by Tsytovich and Akopyan.[1-5*] For an unmagnetized plasma, the photonic growth rate depends on the collective bremsstrahlung probability. Nonlinear bremsstrahlung associated with the three-plasmon dynamic polarization vertex has been shown to make an important contribution to the bremsstrahlung probability.[1,2] In vacuum quantum electrodynamics, because of Furry's theorem,[6] the analogous diagram is vanishing and is therefore absent in the standard Bethe-Heitler bremsstrahlung cross section.[7] In plasma turbulence theory, the collective bremsstrahlung probability depends on the nonlinear bremsstrahlung amplitude through the second-order nonlinear conductivity tensor. The symmetry properties of this tensor are especially important in reducing the complex expression for the collective bremsstrahlung recoil force in a relativistic, weakly turbulent nonequilibrium plasma. The latter is needed to determine the collective bremsstrahlung probability.[1,2] The symmetry properties were documented to some extent by Tsytovich and were shown to be related to the approximate nondissipative nature of the nonlinear current and also to crossing symmetry in three-plasmon interactions.[1,8,9]

The symmetry properties of the nonlinear conductivity tensor have been investigated also in other work. For nonrelativistic, weakly turbulent plasmas, they were established long ago.[10] For relativistic plasmas in which the fields and the particle distributions are such that resonant wave-particle interactions can be ignored, the symmetry relating principal parts only has been demonstrated to all orders.[11-13] Others have investigated also the relationship between the approximate symmetry and the fact that the total energy dissipated by the nonlinear current is vanishing.[8,13,14] The relationship to crossing symmetry was also investigated in analyses of three-wave coupling between Langmuir, sound, and transverse waves.[11,15] The relationship to generalized Onsager relations also has been addressed.[11] The symmetry properties have been related to those of the Poisson brackets in a perturbation-theoretic Hamiltonian formulation.[10,11] Moreover, in coherent three-wave interactions and the weak turbulence equations, it follows from the symmetry properties that wave energy and momentum are approximately conserved, and the Manley-Rowe relations obtain.[10,16-21] To a limited extent, symmetry-breaking effects associated with violation of the Manley-Rowe relations have been addressed.[16,21,22]

**See references in Literature Cited section.*

This paper reports two exact symmetry properties of the nonlinear conductivity tensor for an unmagnetized, relativistic, weakly turbulent plasma. The symmetries are not limited to the principal part. Their principal parts reduce to the well-known approximate symmetry. One of the exact symmetries was obtained previously by using the standard expression for the second-order conductivity tensor in plasma turbulence theory, resulting from straightforward iteration of the Vlasov equation.[14,23-26] However, this symmetry was defined in an unphysical region of wave vector space, at least in its relationship to the second-order nonlinear current density. Another exact symmetry defined in the physical region is developed here. The iterative approach furnishes a new polynomial representation of the second-order conductivity tensor in which all derivatives are removed and the pole structure is clearly exhibited. It is hoped that the present elaboration of these symmetries will facilitate deeper understanding of the collective bremsstrahlung instability and the dissipative properties of the three-plasmon vertex.

In section 2, the polynomial representation of the second-order nonlinear conductivity tensor is presented. In section 3, the exact symmetries and their derivations by means of the polynomial representation are discussed. It is also shown that, ignoring resonant wave-particle interactions, the exact symmetries are reducible to the well-known symmetry relation for the nonrelativistic longitudinal case. In section 4, the results are briefly summarized.

2. POLYNOMIAL REPRESENTATION OF SECOND-ORDER NONLINEAR CONDUCTIVITY TENSOR

The second-order nonlinear conductivity tensor $S_{ijl}(k,k_1,k_2)$ in plasma turbulence theory is defined by[2,14]

$$S_{ijl}\left(k,k_1,k_2\right) = e^2 \int \frac{d^3\vec{p}}{(2\pi)^3} \frac{v_i}{\omega - \vec{k}\cdot\vec{v} + i\delta} \left[\left(\omega_1 - \vec{k}_1\cdot\vec{v}\right)\frac{\partial}{\partial p_j} + v_j k_{1_m}\frac{\partial}{\partial p_m}\right]\left(\frac{\partial}{\partial p_l} + \frac{v_l}{\omega_2 - \vec{k}_2\cdot\vec{v} + i\delta} k_{2_n}\frac{\partial}{\partial p_n}\right) f_p^{R(0)} \tag{1}$$

and is related to the second-order nonlinear current $\vec{j}_k^{(2)}$ by

$$j_{ki}^{(2)} = -e \int \frac{dk_1 dk_2 \delta\left(k-k_1-\kappa_2\right)}{\left(\omega_1 + i\delta\right)\left(\omega_2 + i\delta\right)} S_{ijl}\left(k,k_1,k_2\right) E_{k_1 j} E_{k_2 l} \quad . \tag{2}$$

It should be mentioned here that the tensor defined by equations (18) and (20) of Akopyan and Tsytovich[2] differs implicitly from equation (1) here in that, instead, the first complex denominator $\omega - \vec{k}\cdot\vec{v} + i\delta$ in equation (1) is implicitly $\omega - \vec{k}\cdot\vec{v} - i\delta$ there. The notation of equations (1) and (2) corresponds more directly to equations (10) and (12) of Tsytovich.[27] The symmetries discussed here pertain to the two symmetrized forms

$$\sigma^{\pm}_{ijl}\left(k,k_1,k_2\right) \equiv S_{ijl}\left(k,k_1,k_2\right) \pm S_{ilj}\left(k,k_2 k_1\right) \quad . \tag{3}$$

The tensor $\sigma^{+}_{ijl}(k,k_1,k_2)$ is the same as $\sigma_{ijl}(k,k_1,k_2)$ of earlier work.[14,24,26] It is convenient also to define the antisymmetrized form $\sigma^{-}_{ijl}(k,k_1,k_2)$ above.

First integrating equation (1) by parts, dropping surface terms, then using the relativistic kinetic relations, performing the differentiations, and combining terms, one obtains

$$\begin{aligned} S_{ijl}\left(k,k_1,k_2\right) = e^2 c^2 \int \frac{d^3\vec{p}}{(2\pi)^3} f_p^{R(0)} \frac{1}{\varepsilon^2} \Bigg[& \frac{\alpha_1 + \bar{\alpha}_1\Omega_1}{\Omega + i\delta} + \frac{\alpha_2 + \bar{\alpha}_2\Omega_1}{(\Omega + i\delta)(\Omega_2 + i\delta)} \\ & + \frac{\alpha_3 + \bar{\alpha}_3\Omega_1}{(\Omega + i\delta)(\Omega_2 + i\delta)^2} + \frac{\alpha_4 + \bar{\alpha}_4\Omega_1}{(\Omega + i\delta)^2} \\ & + \frac{\alpha_5 + \bar{\alpha}_5\Omega_1}{(\Omega + i\delta)^2(\Omega_2 + i\delta)} + \frac{\alpha_6 + \bar{\alpha}_6\Omega_1}{(\Omega + i\delta)^2(\Omega_2 + i\delta)^2} \\ & + \frac{\alpha_7 + \bar{\alpha}_7\Omega_1}{(\Omega + i\delta)^3} + \frac{\alpha_8 + \bar{\alpha}_8\Omega_1}{(\Omega + i\delta)^3(\Omega_2 + i\delta)} \Bigg] \ , \end{aligned} \tag{4}$$

where

$$\varepsilon = \left(m^2c^4 + p^2c^2\right)^{1/2} \quad , \tag{5}$$

$$\left\{\Omega,\ \Omega_1,\ \Omega_2\right\} = \left\{\omega - \mu,\ \omega_1 - \mu_1,\ \omega_2 - \mu_2\right\} \quad , \tag{6}$$

$$\left\{\mu,\ \mu_1,\ \mu_2\right\} = \left\{\vec{k}\cdot\vec{v},\ \vec{k}_1\cdot\vec{v},\ \vec{k}_2\cdot\vec{v}\right\} \quad , \tag{7}$$

and where $\{\alpha_n, n = 1, 8\}$ and $\{\bar{\alpha}_n, n = 1, 8\}$ are complicated tensor polynomials in the components of $\vec{v}$, $\vec{k}$, $\vec{k}_1$, and $\vec{k}_2$. They are simply a renaming of the coefficients C_n.[14] For notational convenience, the tensor indices of the $\alpha_n \equiv \alpha_{nijl}(k,k_1,k_2)$ and $\bar{\alpha}_n \equiv \bar{\alpha}_{nijl}(k,k_1,k_2)$ are suppressed. Explicitly, the α_n are given by

$$\alpha_1 = \left(c^2 k_{1_i} - \mu_1 v_i\right)\delta_{jl} - \left(c^2 k_{1_l} - \mu_1 v_l\right)\delta_{ij} - \mu_1 v_j \delta_{il} - 2k_{1_i} v_j v_l + 3c^{-2}\mu_1 v_i v_j v_l \quad , \tag{8}$$

$$\alpha_2 = \left(\mu_1\mu_2 - c^2\vec{k}_1\cdot\vec{k}_2\right) v_l\delta_{ij} + 4c^{-2}\mu_1\mu_2 v_i v_j v_l + c^2 k_{1_i} v_j k_{2_l} + c^2 k_{1_i} k_{2_j} v_l - \mu_1 k_{2_i} v_j v_l - \mu_1 v_i k_{2_j} v_l - \mu_1 v_i v_j k_{2_l} - 3\mu_2 k_{1_i} v_j v_l \quad , \tag{9}$$

$$\alpha_3 = \left(c^2 k_2^2 - \mu_2^2\right) k_{1_i} v_j v_l + \left(c^{-2}\mu_1\mu_2^2 - \mu_1 k_2^2\right) v_i v_j v_l \quad , \tag{10}$$

$$\alpha_4 = \left(c^2\vec{k}\cdot\vec{k}_1 - \mu\mu_1\right)\left(v_i\delta_{jl} + v_j\delta_{il}\right) - c^2 v_i k_j k_{1_l} + \mu_1 v_i k_j v_l - 2\mu_1 v_i v_j k_l - \mu k_{1_i} v_j v_l + c^2 k_{1_i} v_j k_l + \left(5c^{-2}\,\mu\mu_1 - 3\vec{k}\cdot\vec{k}_1\right) v_i v_j v_l \quad , \tag{11}$$

$$\begin{aligned}\alpha_5 = {} & \left(-c^2\vec{k}_1\cdot\vec{k}_2 + \mu_1\mu_2\right) v_i k_j v_l + \left(c^2\vec{k}\cdot\vec{k}_1 - \mu\mu_1\right) v_i v_j k_{2_l} \\ & + \left(c^2\vec{k}\cdot\vec{k}_1 - \mu\mu_1\right) v_i k_{2_j} v_l + \left(c^2\vec{k}\cdot\vec{k}_1 - \mu\mu_1\right) k_{2_i} v_j v_l \\ & + \left(c^2\vec{k}\cdot\vec{k}_2 - \mu\mu_2\right) k_{1_i} v_j v_l + 2\left(3c^{-2}\mu\mu_1\mu_2 - 2\vec{k}\cdot\vec{k}_1\mu_2 \right.\\ & \left. - \vec{k}\cdot\vec{k}_2\mu_1\right) v_i v_j v_l \quad ,\end{aligned} \tag{12}$$

$$\alpha_6 = \left(c^2\vec{k}\cdot\vec{k}_1 k_2^2 - \mu\mu_1 k_2^2 - \vec{k}\cdot\vec{k}_1\mu_2^2 + c^{-2}\mu\mu_1\mu_2^2\right)v_i v_j v_l \quad , \tag{13}$$

$$\alpha_7 = 2\left(c^2\vec{k}\cdot\vec{k}_1 - \mu\mu_1\right)v_i v_j k_l - 2\left(\vec{k}\cdot\vec{k}_1\mu - c^{-2}\mu^2\mu_1\right)v_i v_j v_l \quad , \tag{14}$$

$$\alpha_8 = 2\left(c^2\vec{k}\cdot\vec{k}_1\vec{k}\cdot\vec{k}_2 - \vec{k}\cdot\vec{k}_2\mu\mu_1 - \vec{k}\cdot\vec{k}_1\mu\mu_2 + c^{-2}\mu^2\mu_1\mu_2\right)v_i v_j v_l \quad . \tag{15}$$

The $\bar{\alpha}_n$ are given by

$$\bar{\alpha}_1 = -v_i\delta_{jl} - v_j\delta_{il} - v_l\delta_{ij} + 3c^{-2}v_i v_j v_l \quad , \tag{16}$$

$$\begin{aligned}\bar{\alpha}_2 = {} & \left(c^2 k_{2_l} - 2\mu_2 v_l\right)\delta_{ij} - k_{2_i} v_j v_l - v_i k_{2_j} v_l \\ & - v_i v_j k_{2_l} + 4c^{-2}\mu_2 v_i v_j v_l \quad ,\end{aligned} \tag{17}$$

$$\bar{\alpha}_3 = \left(c^2 k_2^2 - \mu_2^2\right)v_l\delta_{ij} + \left(c^{-2}\mu_2^2 - k_2^2\right)v_i v_j v_l \quad , \tag{18}$$

$$\begin{aligned}\bar{\alpha}_4 = {} & \left(c^2 k_l - \mu v_l\right)\delta_{ij} + \left(c^2 k_j - \mu v_j\right)\delta_{il} - \mu v_i\delta_{jl} \\ & - 2v_i v_j k_l - 2v_i k_j v_l + 5c^{-2}\mu v_i v_j v_l \quad ,\end{aligned} \tag{19}$$

$$\begin{aligned}\bar{\alpha}_5 = {} & \left(c^2\vec{k}\cdot\vec{k}_2 - \mu\mu_2\right)v_l\delta_{ij} + 2\left(3c^{-2}\mu\mu_2 - \vec{k}\cdot\vec{k}_2\right)v_i v_j v_l \\ & + c^2 k_{2_i} k_j v_l + c^2 v_i k_j k_{2_l} \\ & - \mu v_i k_{2_j} v_l - \mu v_i v_j k_{2_l} - \mu k_{2_i} v_j v_l - 3\mu_2 v_i k_j v_l \quad ,\end{aligned} \tag{20}$$

$$\bar{\alpha}_6 = \left(c^2 k_2^2 - \mu_2^2\right) v_i k_j v_l + \left(c^{-2}\mu\mu_2^2 - \mu k_2^2\right) v_i v_j v_l \quad , \tag{21}$$

$$\bar{\alpha}_7 = 2c^2 v_i k_j k_l - 2\mu v_i k_j v_l - 2\mu v_i v_j k_l + 2c^{-2}\mu^2 v_i v_j v_l \quad , \tag{22}$$

$$\bar{\alpha}_8 = 2\left(c^2 \mathbf{k}\cdot\mathbf{k}_2 - \mu\mu_2\right) v_i k_j v_l - 2\left(\mathbf{k}\cdot\mathbf{k}_2\mu - c^{-2}\mu^2\mu_2\right) v_i v_j v_l \quad . \tag{23}$$

The polynomial representation given by equation (4) contains no derivatives, and the explicit pole structure is clearly exhibited. In section 3, equation (4) is used to obtain the exact symmetries.

3. THE EXACT SYMMETRIES

In this section, the polynomial representation, equation (4), of the nonlinear conductivity tensor is used to explicitly establish the following exact symmetries in wave vector space:

$$\sigma^{\ddagger}_{ijl}\left(\pm k_1 \pm k_2, k_1, k_2\right) = \sigma^{\mp}_{jil}\left(k_1, \pm k_1 \pm k_2, k_2\right) \quad . \tag{24}$$

The one involving $\sigma^{+}_{ijl}(-k_1 -k_2, k_1, k_2)$ was obtained previously. The one involving $\sigma^{+}_{ijl}(k_1 +k_2, k_1, k_2)$ occurs in the physical region of wave vector space of equation (2) and is therefore of greater interest.

First replacing k by $\pm k_1 \pm k_2$ in equation (4) and then combining terms, one obtains

$$\sigma^{\ddagger}_{ijl}\left(\pm k_1 \pm k_2, k_1, k_2\right)$$

$$= e^2 c^2 \int \frac{d^3 p}{(2\pi)^3} \frac{f_p^{R(0)} \sum_{n=1}^{24} \beta_n \Pi_n}{\varepsilon^2 \left(\pm\Omega_1 \pm\Omega_2 + i\delta\right)^3 \left(\Omega_1 + i\delta\right)^3 \left(\Omega_2 + i\delta\right)^3} \quad , \tag{25}$$

where

$$\left\{\Pi_n,\ n = 1,\ 24\right\} = \left\{\Omega_1\Omega_2^4,\ \Omega_1\Omega_2^5,\ \Omega_1\Omega_2^6,\ \Omega_1^2\Omega_2^3,\ \Omega_1^2\Omega_2^4,\ \Omega_1^2\Omega_2^5,\ \Omega_1^2\Omega_2^6,\ \Omega_1^3\Omega_2^2,\right.$$
$$\Omega_1^3\Omega_2^3,\ \Omega_1^3\Omega_2^4,\ \Omega_1^3\Omega_2^5,\ \Omega_1^3\Omega_2^6,\ \Omega_1^4\Omega_2,\ \Omega_1^4\Omega_2^2,\ \Omega_1^4\Omega_2^3,\ \Omega_1^4\Omega_2^4, \tag{26}$$
$$\left.\Omega_1^4\Omega_2^5,\ \Omega_1^5\Omega_2,\ \Omega_1^5\Omega_2^2,\ \Omega_1^5\Omega_2^3,\ \Omega_1^5\Omega_2^4,\ \Omega_1^6\Omega_2,\ \Omega_1^6\Omega_2^2,\ \Omega_1^6\Omega_2^3\right\} ,$$

and where $\{\beta_n,\ n = 1,\ 24\}$ are complicated tensor polynomials in the components of $\vec{v}$, $\vec{k}_1$, and $\vec{k}_2$. The latter are given by

$$\beta_1 = \left(c^2k_1^2k_2^2 + c^2\vec{k}_1\cdot\vec{k}_2k_1^2 - \mu_2^2k_1^2 - \mu_1\mu_2k_1^2 - \mu_1^2\vec{k}_1\cdot\vec{k}_2\right.$$
$$\left. - \mu_1^2k_2^2 + c^{-2}\mu_1^2\mu_2^2 + c^{-2}\mu_1^3\mu_2\right) v_iv_jv_l \quad , \tag{27}$$

$$\beta_2 = \left(c^2k_1^2 - \mu_1^2\right)k_{1_l}v_iv_j + \left(c^2k_1^2 - \mu_1^2\right)k_{2_l}v_iv_j$$
$$+ \left(c^2k_1^2 - \mu_1^2\right)k_{2_i}v_jv_l + \left(-2\mu_2k_1^2 - \mu_1k_1^2 + 2c^{-2}\mu_1^2\mu_2\right. \tag{28}$$
$$\left. + c^{-2}\mu_1^3\right)v_iv_jv_l \quad ,$$

$$\beta_3 = \left(c^2k_1^2 - \mu_1^2\right)v_j\delta_{il} - \left(k_1^2 - c^{-2}\mu_1^2\right)v_iv_jv_l \quad , \tag{29}$$

$$\beta_4 = \left[3c^2k_1^2k_2^2 + 2c^2k_2^2\vec{k}_1\cdot\vec{k}_2 + 2c^2\left(\vec{k}_1\cdot\vec{k}_2\right)^2 + 3c^2k_1^2\vec{k}_1\cdot\vec{k}_2\right.$$
$$- 3k_1^2\mu_2^2 - 3k_1^2\mu_1\mu_2 - 2\vec{k}_1\cdot\vec{k}_2\mu_2^2 - 4\vec{k}_1\cdot\vec{k}_2\mu_1\mu_2$$
$$- 2k_2^2\mu_1\mu_2 - 3k_2^2\mu_1^2 - 3\vec{k}_1\cdot\vec{k}_2\mu_1^2 + 2c^{-2}\mu_1\mu_2^3 \tag{30}$$
$$\left. + 5c^{-2}\mu_1^2\mu_2^2 + 3c^{-2}\mu_1^3\mu_2\right]v_iv_jv_l \quad ,$$

$$
\begin{aligned}
\beta_5 = {} & \Big(2c^2\vec{k}_1\cdot\vec{k}_2 k_{1_1} + 3c^2k_1^2k_{1_1} - 2\mu_1\mu_2k_{1_1} - 3\mu_1^2k_{1_1} \\
& + c^2\vec{k}_1\cdot\vec{k}_2k_{2_1} - \mu_2^2k_{1_1} - \mu_1\mu_2k_{2_1} + c^2k_2^2k_{1_1} \\
& + 3c^2k_1^2k_{2_1} - 3\mu_1^2k_{2_1}\Big)v_iv_j \\
& + \Big(c^2\vec{k}_1\cdot\vec{k}_2k_{1_i} - \mu_1\mu_2k_{1_i} + c^2\vec{k}_1\cdot\vec{k}_2k_{2_i} - \mu_1\mu_2k_{2_i} \\
& + c^2k_2^2k_{1_i} - \mu_2^2k_{1_i} + 3c^2k_1^2k_{2_i} - 3\mu_1^2k_{2_i}\Big)v_jv_1 \\
& + \Big(c^2\vec{k}_1\cdot\vec{k}_2k_{1_j} - \mu_1\mu_2k_{1_j} + c^2k_2^2k_{1_j} - \mu_2^2k_{1_j}\Big)\ v_iv_1 \\
& + \Big(-6\vec{k}_1\cdot\vec{k}_2\mu_1 + 13c^{-2}\mu_1^2\mu_2 - 3k_1^2\mu_1 + 3c^{-2}\mu_1^3 \\
& - 7k_1^2\mu_2 - 4\vec{k}_1\cdot\vec{k}_2\mu_2 - 4k_2^2\mu_1 + 8c^{-2}\mu_1\mu_2^2\Big)v_iv_jv_1 \quad ,
\end{aligned} \tag{31}
$$

$$
\begin{aligned}
\beta_6 = {} & \Big(-3\mu_1^2 + 3c^2k_1^2\Big)v_j\delta_{i1} + \Big(c^2k_{2_1}k_{1_j} + c^2k_{1_1}k_{1_j}\Big)v_i \\
& + \Big(c^2k_{2_1}k_{1_i} + c^2k_{1_1}k_{1_i} + c^2k_{1_1}k_{2_i}\Big)v_j + c^2k_{2_i}k_{1_j}v_1 \\
& + \Big(-2\mu_2k_{1_1} - 4\mu_1k_{1_1} - 3\mu_1k_{2_1}\Big)v_iv_j \\
& + \Big(-2\mu_2k_{1_j} - \mu_1k_{1_j}\Big)v_iv_1 + \Big(-2\mu_2k_{1_i} - \mu_1k_{1_i} - 3\mu_1k_{2_i}\Big)v_jv_1 \\
& + \Big(-4k_1^2 + 10c^{-2}\mu_1\mu_2 + 8c^{-2}\mu_1^2 - 2\vec{k}_1\cdot\vec{k}_2\Big)v_iv_jv_1 \quad ,
\end{aligned} \tag{32}
$$

$$
\begin{aligned}
\beta_7 = {} & \Big(-2\mu_1v_j + c^2k_{1_j}\Big)\delta_{i1} - k_{1_i}v_jv_1 - k_{1_1}v_iv_j \\
& - k_{1_j}v_iv_1 + 4c^{-2}\mu_1v_iv_jv_1 \quad ,
\end{aligned} \tag{33}
$$

$$
\begin{aligned}
\beta_8 = \Big[& 3c^2k_1^2k_2^2 + 2c^2k_1^2\vec{k}_1\cdot\vec{k}_2 + 3c^2\vec{k}_2^2\vec{k}_1\cdot\vec{k}_2 + 2c^2\left(\vec{k}_1\cdot\vec{k}_2\right)^2 \\
& - 3k_2^2\mu_1^2 - 3k_2^2\mu_1\mu_2 - 2\vec{k}_1\cdot\vec{k}_2\mu_1^2 - 4\vec{k}_1\cdot\vec{k}_2\mu_1\mu_2 \\
& - 2k_1^2\mu_1\mu_2 - 3k_1^2\mu_2^2 - 3\vec{k}_1\cdot\vec{k}_2\mu_2^2 + 2c^{-2}\mu_1^3\mu_2 \\
& + 5c^{-2}\mu_1^2\mu_2^2 + 3c^{-2}\mu_1\mu_2^3\Big] v_i v_j v_l \quad ,
\end{aligned} \tag{34}
$$

$$
\begin{aligned}
\beta_9 = \Big(& 3c^2k_1^2k_{2_l} + 2c^2\vec{k}_1\cdot\vec{k}_2k_{2_l} - 3\mu_1^2k_{2_l} - 2\mu_1\mu_2k_{2_l} \\
& + 2c^2k_1^2k_{1_l} + 2c^2\vec{k}_1\cdot\vec{k}_2k_{1_l} - 2\mu_1^2k_{1_l} + c^2k_2^2k_{1_l} \\
& - 2\mu_1\mu_2k_{1_l} - \mu_2^2k_{1_l}\Big)v_iv_j + \Big(c^2k_1^2k_{2_j} + 2c^2\vec{k}_1\cdot\vec{k}_2k_{2_j} \\
& + 2c^2k_2^2k_{2_j} - \mu_1^2k_{2_j} - 2\mu_1\mu_2k_{2_j} - 2\mu_2^2k_{2_j} + 2c^2\vec{k}_1\cdot\vec{k}_2k_{1_j} \\
& - 2\mu_1\mu_2k_{1_j} + 3c^2k_2^2k_{1_j} - 3\mu_2^2k_{1_j}\Big)v_iv_l \\
& + \Big(2c^2\vec{k}_1\cdot\vec{k}_2k_{1_i} - 2\mu_1\mu_2k_{1_i} + 3c^2k_2^2k_{1_i} - 3\mu_2^2k_{1_i} \\
& + 3c^2k_1^2k_{2_i} + 2c^2\vec{k}_1\cdot\vec{k}_2k_{2_i} - 3\mu_1^2k_{2_i} - 2\mu_1\mu_2k_{2_i}\Big)v_jv_l \\
& + \Big(-10\vec{k}_1\cdot\vec{k}_2\mu_1 - 9k_1^2\mu_2 - 10\vec{k}_1\cdot\vec{k}_2\mu_2 + 19c^{-2}\mu_1\mu_2^2 \\
& + 19c^{-2}\mu_2\mu_1^2 - 2\mu_2k_2^2 + 2c^{-2}\mu_2^3 - 9\mu_1k_2^2 - 2\mu_1k_1^2 \\
& + 2c^{-2}\mu_1^3\Big)v_iv_jv_l \quad ,
\end{aligned} \tag{35}
$$

$$\beta_{10} = \left(c^2k_1^2 + 2c^2\vec{k}_1\cdot\vec{k}_2 - \mu_1^2 - 2\mu_1\mu_2 + c^2k_2^2 - \mu_2^2\right)v_i\delta_{jl}$$

$$+ \left(-3\mu_1^2 + 3c^2k_1^2\right)v_j\delta_{il} + \left(c^2k_2^2 - \mu_2^2\right)v_l\delta_{ij}$$

$$+ \left(2c^2k_{1_l}k_{1_j} + c^2k_{2_j}k_{2_l} + 3c^2k_{1_j}k_{2_l}\right)v_i$$

$$+ \left(2c^2k_{1_l}k_{1_i} + 2c^2k_{2_i}k_{1_l} + 3c^2k_{2_l}k_{1_i}\right)v_j$$

$$+ \left(c^2k_{1_i}k_{2_j} + c^2k_{2_j}k_{2_i} + 3c^2k_{1_j}k_{2_i}\right)v_l \tag{36}$$

$$+ \left(-8\mu_1k_{1_l} - 8\mu_1k_{2_l} - \mu_2k_{2_l} - 4\mu_2k_{1_l}\right)v_iv_j$$

$$+ \left(-2\mu_1k_{1_i} - 7\mu_2k_{1_i} - 8\mu_1k_{2_i} - \mu_2k_{2_i}\right)v_jv_l$$

$$+ \left(-2\mu_1k_{2_j} - 2\mu_1k_{1_j} - 7\mu_2k_{1_j} - 4\mu_2k_{2_j}\right)v_iv_l$$

$$+ \left(14c^{-2}\mu_1^2 + 32c^{-2}\mu_1\mu_2 - 8\vec{k}_1\cdot\vec{k}_2 - 6k_1^2\right.$$

$$\left. - 3k_2^2 + 7c^{-2}\mu_2^2\right)v_iv_jv_l \quad ,$$

$$\beta_{11} = \left(c^2k_{1_i} + c^2k_{2_i} - 2\mu_1v_i - 2\mu_2v_i\right)\delta_{jl}$$

$$+ \left(c^2k_{2_l} - 2\mu_2v_l\right)\delta_{ij} + \left(3c^2k_{1_j} - 6\mu_1v_j\right)\delta_{il}$$

$$- 2\left(k_{2_l} + 2k_{1_l}\right)v_iv_j - 2\left(2k_{1_i} + k_{2_i}\right)v_jv_l \tag{37}$$

$$- 2\left(k_{2_j} + 2k_{1_j}\right)v_lv_i + 8\left(\mu_2 + 2\mu_1\right)c^{-2}v_iv_jv_l \quad ,$$

$$\beta_{12} = \left(-v_i\delta_{jl} - v_l\delta_{ij} - v_j\delta_{il} + 3c^{-2}v_iv_jv_l\right) \quad , \tag{38}$$

$$
\begin{aligned}
\beta_{13} = \Big(&c^2k_1^2k_2^2 + c^2\mathbf{k}_1\cdot\mathbf{k}_2k_2^2 - \mu_1^2k_2^2 - \mu_1\mu_2k_2^2 - \mu_2^2\mathbf{k}_1\cdot\mathbf{k}_2 \\
&- \mu_2^2k_1^2 + c^{-2}\mu_2^2\mu_1^2 + c^{-2}\mu_1\mu_2^3\Big)v_iv_jv_l \quad ,
\end{aligned} \tag{39}
$$

$$
\begin{aligned}
\beta_{14} = \Big(&c^2\mathbf{k}_1\cdot\mathbf{k}_2k_{1_i} - \mu_1\mu_2k_{1_i} + 3c^2k_2^2k_{1_i} - 3\mu_2^2k_{1_i} + c^2k_1^2k_{2_i} \\
&+ c^2\mathbf{k}_1\cdot\mathbf{k}_2k_{2_i} - \mu_1^2k_{2_i} - \mu_1\mu_2k_{2_i}\Big)v_jv_l \\
&+ \Big(c^2k_1^2k_{2_l} - \mu_1\mu_2k_{2_l} + c^2\mathbf{k}_1\cdot\mathbf{k}_2k_{2_l} - \mu_1^2k_{2_l}\Big)v_iv_j \\
&+ \Big(c^2k_1^2k_{2_j} + 2c^2\mathbf{k}_1\cdot\mathbf{k}_2k_{2_j} - \mu_1^2k_{2_j} - 2\mu_1\mu_2k_{2_j} + c^2\mathbf{k}_1\cdot\mathbf{k}_2k_{1_j} \\
&- \mu_1\mu_2k_{1_j} + 3c^2k_2^2k_{1_j} + 3c^2k_2^2k_{2_j} - 3\mu_2^2k_{1_j} - 3\mu_2^2k_{2_j}\Big)v_iv_l \\
&+ \Big(-6\mathbf{k}_1\cdot\mathbf{k}_2\mu_2 - 4k_1^2\mu_2 + 8c^{-2}\mu_1^2\mu_2 - 7k_2^2\mu_1 - 3k_2^2\mu_2 \\
&+ 13c^{-2}\mu_1\mu_2^2 + 3c^{-2}\mu_2^3 - 4\mathbf{k}_1\cdot\mathbf{k}_2\mu_1\Big)v_iv_jv_l \quad ,
\end{aligned} \tag{40}
$$

$$
\begin{aligned}
\beta_{15} = &\Big(-\mu_1^2 + c^2k_1^2\Big)v_j\delta_{il} + \Big(-3\mu_2^2 + 3c^2k_2^2\Big)v_l\delta_{ij} \\
&+ \Big(-\mu_1^2 - 2\mu_1\mu_2 + c^2k_1^2 + 2c^2k_1\cdot k_2 - \mu_2^2 + c^2k_2^2\Big)v_i\delta_{jl} \\
&+ c^2\Big(k_{1_j}k_{1_l} + 3k_{1_j}k_{2_l} + 2k_{2_j}k_{2_l}\Big)v_i \\
&+ c^2\Big(k_{1_i}k_{1_l} + 3k_{1_i}k_{2_l} + k_{2_i}k_{1_l}\Big)v_j \\
&+ c^2\Big(2k_{2_i}k_{2_j} + 3k_{2_i}k_{1_j} + 2k_{1_i}k_{2_j}\Big)v_l \\
&+ \Big(-7\mu_1k_{2_l} - 2\mu_2k_{2_l} - 4\mu_1k_{1_l} - 2\mu_2k_{1_l}\Big)v_iv_j \\
&+ \Big(-\mu_1k_{1_j} - 8\mu_2k_{1_j} - 8\mu_2k_{2_j} - 4\mu_1k_{2_j}\Big)v_iv_l \\
&+ \Big(-\mu_1k_{1_i} - 8\mu_2k_{1_i} - 2\mu_2k_{2_i} - 7\mu_1k_{2_i}\Big)v_jv_l \\
&+ \Big(7c^{-2}\mu_1^2 + 32c^{-2}\mu_1\mu_2 + 14c^{-2}\mu_2^2 - 3k_1^2 - 8\mathbf{k}_1\cdot\mathbf{k}_2 \\
&- 6k_2^2\Big)v_iv_jv_l \quad ,
\end{aligned} \tag{41}
$$

$$\beta_{16} = 2\left(c^2k_{1_i} + c^2k_{2_i}\right)\delta_{jl} + 3c^2k_{2_l}\delta_{ij} + 3c^2k_{1_j}\delta_{il}$$
$$- 6\mu_1 v_j\delta_{il} - 6\mu_2 v_l\delta_{ij} - 4\left(\mu_1 + \mu_2\right)v_i\delta_{jl} - 5\left(k_{1_l} + k_{2_l}\right)v_iv_j$$
$$- 5\left(k_{1_i} + k_{2_i}\right)v_jv_l - 5\left(k_{1_j} + k_{2_j}\right)v_iv_l \tag{42}$$
$$+ 20\left(c^{-2}\mu_1 + c^{-2}\mu_2\right)v_iv_jv_l \quad ,$$

$$\beta_{17} = -3v_i\delta_{jl} - 3v_l\delta_{ij} - 3v_j\delta_{il} + 9c^{-2}v_iv_jv_l \quad , \tag{43}$$

$$\beta_{18} = \left(c^2k_2^2k_{1_j} + c^2k_2^2k_{2_j} - \mu_2^2k_{1_j} - \mu_2^2k_{2_j}\right)v_iv_l$$
$$+ \left(2c^{-2}\mu_1\mu_2^2 + c^{-2}\mu_2^3 - 2\mu_1k_2^2 - \mu_2k_2^2\right)v_iv_jv_l \tag{44}$$
$$+ \left(c^2k_2^2 - \mu_2^2\right)k_{1_i}v_jv_l \quad ,$$

$$\beta_{19} = c^2k_{1_i}k_{2_l}v_j + \left(c^2k_{1_i}k_{2_j} + c^2k_{1_j}k_{2_i} + c^2k_{2_j}k_{2_i}\right)v_l$$
$$+ \left(c^2k_{1_j}k_{2_l} + c^2k_{2_j}k_{2_l}\right)v_i + \left(3c^2k_2^2 - 3\mu_2^2\right)v_l\delta_{ij}$$
$$- \left(\mu_2k_{2_l} + 2\mu_1k_{2_l}\right)v_iv_j - \left(\mu_2k_{2_i} + 2\mu_1k_{2_i} + 3\mu_2k_{1_i}\right)v_jv_l \tag{45}$$
$$- \left(2\mu_1k_{2_j} + 3\mu_2k_{1_j} + 4\mu_2k_{2_j}\right)v_iv_l$$
$$+ 2\left(5c^{-2}\mu_1\mu_2 - 2k_2^2 + 4c^{-2}\mu_2^2 - \vec{k}_1\cdot\vec{k}_2\right)v_iv_jv_l \quad ,$$

$$\beta_{20} = \left(3c^2k_{2_l} - 6\mu_2v_l\right)\delta_{ij} + \left(c^2k_{1_j} - 2\mu_1v_j\right)\delta_{il}$$
$$+ \left(c^2k_{1_i} + c^2k_{2_i} - 2\mu_1v_i - 2\mu_2v_i\right)\delta_{jl}$$
$$+ 8\left(c^{-2}\mu_1 + 2c^{-2}\mu_2\right)v_iv_jv_l - 2\left(k_{1_j} + 2k_{2_j}\right)v_iv_l \tag{46}$$
$$- 2\left(k_{1_l} + 2k_{2_l}\right)v_iv_j - \left(2\,k_{1_i} + 2k_{2_i}\right)v_jv_l \quad ,$$

$$\beta_{21} = -3v_i\delta_{jl} - 3v_j\delta_{il} - 3v_l\delta_{ij} + 9c^{-2}v_iv_jv_l \quad , \tag{47}$$

$$\beta_{22} = \left(c^2k_2^2 - \mu_2^2\right)v_l\delta_{ij} + \left(c^{-2}\mu_2^2 - k_2^2\right)v_iv_jv_l \quad , \tag{48}$$

$$\begin{aligned}\beta_{23} = &\left(-2\mu_2 v_l + c^2 k_{2_l}\right)\delta_{ij} - k_{2_i}v_jv_l - k_{2_j}v_iv_l \\ &- k_{2_l}v_iv_j + 4c^{-2}\mu_2 v_iv_jv_l \quad ,\end{aligned} \tag{49}$$

$$\beta_{24} = -v_i\delta_{jl} - v_j\delta_{il} - v_l\delta_{ij} + 3c^{-2}v_iv_jv_l \quad . \tag{50}$$

Similarly, by reducing $(\sigma^{\mp}_{jil}(-k_1,\mp k_1 \mp k_2,-k_2))^*$, comparing the result with equation (25) term by term, and then using the reality property of the current and the electric field, the exact symmetry relations given by equations (24) follow.

The principal parts of equations (24) correspond to the well-known symmetry of the second-order nonlinear conductivity tensor. This correspondence results from ignoring resonant wave-particle interactions. In that case, the well-known symmetry relation for the nonrelativistic longitudinal case, equation (2.83) of Tsytovich,[9] also follows. To see this, one first notes that the pure longitudinal nonrelativistic second-order conductivity S_{k,k_1,k_2} is given by[9]

$$S_{k,k_1,k_2} = -\frac{e^3}{|\vec{k}|\ |\vec{k}_1|\ |\vec{k}_2|}\int \frac{\vec{k}\cdot\vec{v}}{\omega - \vec{k}\cdot\vec{v} + i\delta}\left(\vec{k}_1\cdot\nabla_p\right)\frac{1}{\omega_2 - \vec{k}_2\cdot\vec{v} + i\delta} \times \left(\vec{k}_2\cdot\vec{\nabla}_p\right)f_p^{R(0)}\ \frac{d^3\vec{p}}{(2\pi)^3} \quad . \tag{51}$$

Comparing equation (51) with equation (1) then yields

$$S_{k,k_1,k_2} = -e\,\frac{k_i}{|\vec{k}|}\,\frac{k_{1_j}}{|\vec{k}_1|}\,\frac{k_{2_l}}{|\vec{k}_2|}\cdot\frac{1}{\omega_1\omega_2}\,S_{ijl}\left(k,k_1,k_2\right) \quad . \tag{52}$$

By using equation (3) and equation (52), it follows that

$$\frac{1}{\omega_2}\left(S_{k_2,k_1+k_2,-k_1} + S_{k_2,-k_1,k_1+k_2}\right)$$

$$= -e\,\frac{\left(k_{1_j} + k_{2_j}\right)k_{1_l}k_{2_i}\sigma^{+}_{ijl}\left(k_2,k_1+k_2,-k_1\right)}{\left|\vec{k}_1 + \vec{k}_2\right|\,\left|\vec{k}_1\right|\,\left|\vec{k}_2\right|\,\left(\omega_1 + \omega_2\right)\omega_1\omega_2} \tag{53}$$

and

$$-\frac{1}{\omega_1 + \omega_2}\left(S_{-k_1-k_2,-k_1,-k_2} + S_{-k_1-k_2,-k_2,-k_1}\right)$$

$$= -e\,\frac{\left(k_{1_j} + k_{2_j}\right)k_{1_l}k_{2_i}\sigma^{+}_{jil}\left(-k_1-k_2,-k_2,-k_1\right)}{\left|\vec{k}_1 + \vec{k}_2\right|\,\left|\vec{k}_1\right|\,\left|\vec{k}_2\right|\,\left(\omega_1 + \omega_2\right)\omega_1\omega_2}\ . \tag{54}$$

If one ignores the imaginary part δ in equation (1), then using equation (3) one immediately obtains the following approximate relation:

$$\sigma^{+}_{ijl}\left(-k,k_1,k_2\right) \approx -\sigma^{+}_{ijl}\left(k,k_1,k_2\right)\ . \tag{55}$$

By using equation (55) together with one of the exact symmetry relations equations (24), it follows that

$$\sigma^{+}_{jil}\left(-k_1-k_2,-k_2,-k_1\right) \approx \sigma^{+}_{ijl}\left(k_2,k_1+k_2,-k_1\right)\ . \tag{56}$$

Substituting equation (56) into equation (54) and comparing the result with equation (53), one obtains

$$\frac{1}{\omega_2}\left(S_{k_2,k_1+k_2,-k_1} + S_{k_2,-k_1,k_1+k_2}\right)$$
$$\approx -\frac{1}{\omega_1 + \omega_2}\left(S_{-k_1-k_2,-k_1,-k_2} + S_{-k_1-k_2,-k_2,-k_1}\right)\ . \tag{57}$$

Equation (57) is the well-known symmetry relation for the nonrelativistic longitudinal case (eq (2.83) of Tsytovich[9]). Ignoring the imaginary part δ in equation (55) is equivalent to ignoring resonant wave-particle interactions and including only the principal part. The approximate symmetry can also be shown to follow from the other exact symmetry of equations (24).

4. CONCLUSION

In conclusion then, the following exact symmetry relations hold for the second-order nonlinear conductivity tensor of an unmagnetized relativistic weakly turbulent plasma:

$$\sigma^{\pm}_{ijl}\left(\pm k_1 \pm k_2, k_1, k_2\right) = \sigma^{\mp}_{jil}\left(k_1, \pm k_1 \pm k_2, k_2\right) \quad , \tag{58}$$

where $\sigma^{\pm}_{ijl}(k, k_1, k_2)$ are defined by equations (1) and (3). Also, a polynomial representation, equation (4), for the tensor has been obtained in which all derivatives are removed and the pole structure is clearly exhibited. The principal part of the exact symmetries, equation (58), is the well-known approximate symmetry that applies when resonant wave-particle interactions are negligible, the Manley-Rowe relations obtain, and the nonlinear current is nondissipative.

The symmetry properties are especially useful in the calculation of the bremsstrahlung recoil force in a relativistic nonequilibrium plasma. The latter is necessary to determine the collective bremsstrahlung probability and to investigate the conditions for the occurrence of a bremsstrahlung instability.[28]

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